Investigating Bathymetric Assumptions in Acoustic Modeling

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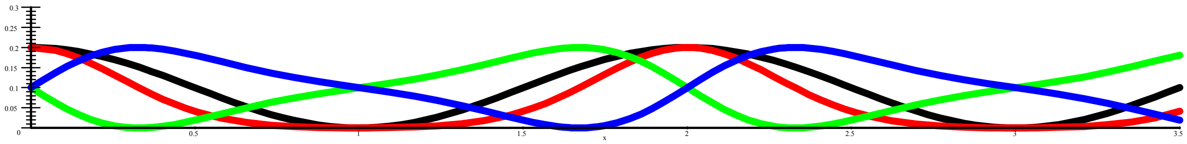
Abstract

How well a computer model represents the real world depends in part on the validity of the assumptions and approximations used. We have used HPC (high performance computing) resources to explore some of those concerning bathymetry as applied in acoustic models of sonar operations. Of the four studied, one was supported, two failed, and the last was supported for certain situations.

Motivation

One task of naval operations is landing personnel and equipment on hostile shores, preferably with a minimum of loss. Sonar performance modeling and prediction is intended to increase target detection probability thereby decreasing the probability of loss of life and equipment. Consequently, improving sonar performance predictions and increasing the probability of locating targets in littoral waters is a goal of naval research. Computer models of most real systems contain simplifying assumptions and approximations that make representing complex systems possible. How well such assumptions and approximations represent the real world determine how well the model performs. Acoustic models are no exception. In naval mine hunting tasks, mines are generally near or on the sea floor or buried by the sea floor material. Therefore, assumptions and approximations related to the structure and behavior of the sea floor material are significant. This project is designed to test some of the assumptions inherent in acoustic models and the bathymetry models or representations used in conjunction with them concerning sea floor bathymetry in regions dominated by sand. The goal is identifying which of the assumptions are valid and exploring ways of improving those that are insufficiently represented. The pertinent assumptions include: i. Bathymetric features smaller than the sonar pulse length (in meters) are insignificant; ii. All bathymetric features are encountered head-on (acoustic path is perpendicular to the sand wave crest); iii. Contributions from sonar sidelobes are negligible; and iv. all sand wave profiles may be represented as sinusoidal (root mean square (rms) roughness). This study concentrates on the effects of azimuth angle, the angle between the observation path and the normal to the sand wave crest, sand wave profile symmetry, and dip angle, the angle between the horizontal and the observation path, on backscattered acoustic intensity. All of these effects are studied within the context of the assumptions that sand behaves as a hard surface and single scattering.



1. Example profiles used in the sand waves in this study. The four profiles included are sine wave (black), symmetric sand wave (red), forward facing asymmetric sand wave (green) and backward facing asymmetric sand wave (blue).

Methodology and HPC Resources

Model seafloors are constructed using the Bathymetry Generation Model module, BaGM-3D [1]. The seafloor files, approximately 56 Mb in size, are then transferred to the Naval Oceanographic Office High Performance Computing (NAVO HPC) center's Cray SV1 at Stennis Space Center, MS where they are evaluated using the Wedge Assemblage Scattering Program (WASP) [2]. Each seafloor is analyzed with WASP for the relative backscattered acoustic intensity of co-located source and receiver at three dip angles and six azimuth angles. A data set consists of WASP runs for each of the 18 dip and azimuth angle combinations . Analysis is performed on the averaged results of 5 to 20 data sets from seafloors constructed using the same input parameters. Averaging is essential to producing usable results by reducing noise in output.

BaGM is a deterministic sand wave model that is used to construct sand wave and ripple patterns, including composite patterns. The minimum size of a generated bathymetric feature is determined by the selected step size, while the maximum size is determined by computational resources, time constraints, and desired resolution. Sand wave length, wave height, profile symmetry, and orientation are all user selected. Because BaGM is deterministic, consideration for multiple seafloors generated with the same parameters is made by the use of certain randomizing factors applied to input parameters. For example, suppose we are representing a sand wave field consisting of short-crested sand waves with some typical crest-to-crest sand wavelength. In the real sand wave field, the actual wavelengths and relative starting position with respect to the observer would randomly vary around the average or measured value. With BaGM, such random variation is introduced by turning on flags that allow for randomized variation of certain "typical" values. BaGM can make a wide variety of sand ripple patterns ranging from very simple long crested sand waves/ripples to cuspate sand ripples, all with varying profile symmetries.

The bathymetric sand ripple pattern emphasized in this study is long-crested. Long-crested sand waves and ripples are defined by Inman as sand ripples having crest lengths greater than 8 times the sand wavelength or crest-to-crest distance. For the purposes of this paper, long-crested sand ripples span the observation patch. This pattern choice makes isolating the effects of changes in the source/ receiver position or sand ripple profile easier to isolate from other possible effects. Along with a pure sine wave, three sand ripple profile symmetries are considered in this study. They are wave-generated symmetric and the two opposing asymmetric current or wave/current profile symmetries (see Figure 1). The sand wavelength is 2 meters, slightly larger than typical sonar pulse lengths, but smaller than can be represented in most sonar performance models. The step size is .005 meters, with patch size 2048 by 2048 steps or approximately 10 $\times$ 10 meters.

The Wedge Assemblage Scattering Program (WASP) is a time domain approach for calculating the acoustic (finite) impulse response of impenetrable two-dimensional (2D) surfaces. It is based on Biot-Tolstoy's solution for the impulse response of an infinite impenetrable wedge [3] and has been tested and found in good agreement with numerous studies involving measured data and high accuracy numerical solutions, including [4] a state-of-the-art frequency domain method for the problem of backscattering from 2D sea surfaces. It works by breaking the surface down into triangular facets, defined by two adjacent points and the virtual point found by interpolating the defined values of these and the other two points in the unit cell. A wedge is then defined by the intersection of two facets. The output are binary files of scattered pressure verses time curves. WASP is a vectorized, single processor program installed on the NAVO HPC Cray SV1 at Stennis Space Center, MS. It is estimated that the time saved in using the vectorized machine is an order of magnitude.

Each WASP run for a single dip and azimuth angle usually takes between 10 and 30 minutes, depending on the number of bathymetery points and the number of points in the discrete time series. Consequently, a complete data set of 20 seafloors, evaluated at the 18 different angular combinations can take over a week to complete, though the typical run time is three to five days. The binary time series produced by the program are Fourier transformed to the frequency domain with the output displayed as relative scattered intensity verses frequency.

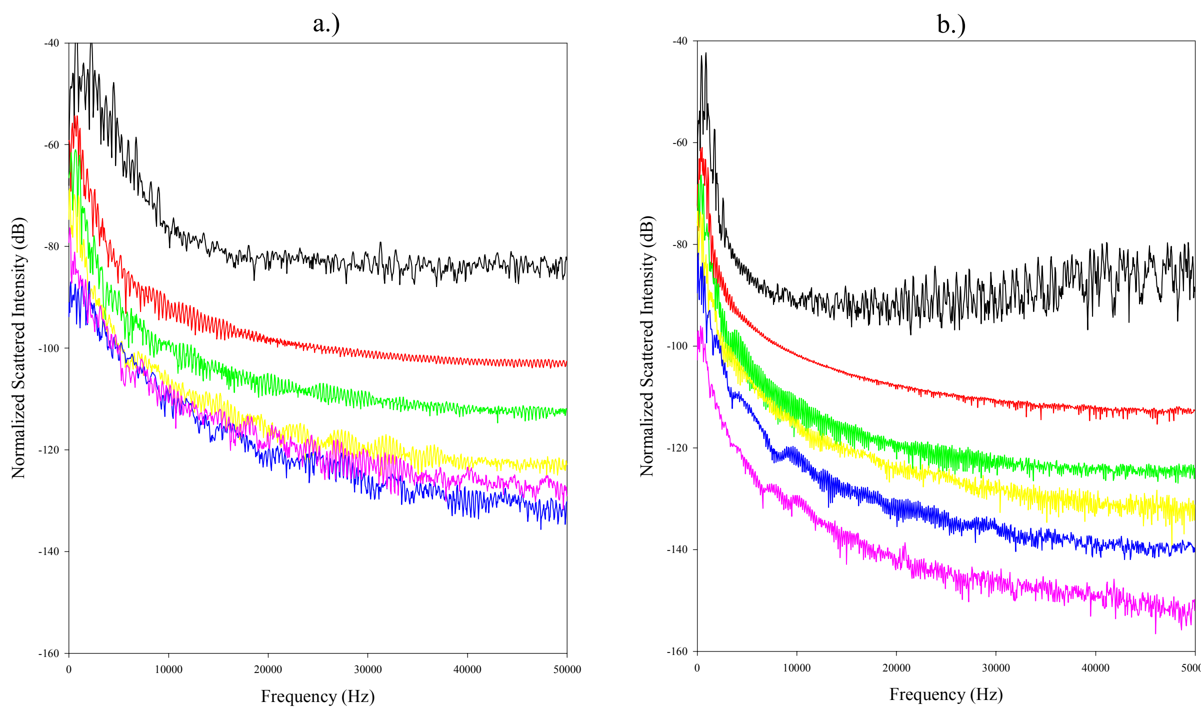
For a given time interval, the step size of the seafloor determines the maximum applicable frequency. In this case, the time interval sets an upper frequency limit of 50 kHz while the sea floor step size of .005 m translates to a maximum frequency of 35 kHz. In typical mine hunting sonar operations, this is actually a relatively low frequency, however decreasing the step size to increase the maximum frequency results in either a significantly smaller patch or significantly greater computational time for the same size patch. A smaller patch means increased probability of errors due to truncating the time series, while reducing the step size by only $\frac{1}{2}$ to 0.0025 m, for a 10×10 patch increases the computation time by 4.

Results and Analysis

In general, acoustic measurements that all fall within 6 dB of one another are taken to be consistent. Using this 6 dB convention for defining the validity of an approximation or assumption, we will say that when varying a parameter produces less than a 6 dB variation in the results, then the assumption or approximation based on that parameter is valid. By the same token, contributions to the signal that are 20 or more dB down from the main beam are negligible. In this study, azimuth angle is measured in the horizontal with 0 degrees defined as perpendicular to the dominant sand wave crest direction and 90 degrees parallel to the sand wave crest. Dip angle is measured in the vertical increasing down towards the sea floor.

In previously obtained results, it was found that the addition of small random noise features to the surface of a modeled sand ripple can cause an increase in the relative backscattered intensity of up to 60 dB [5, 6]. Although these results are exaggerated over what would be found in a real situation, they clearly demonstrate that neglecting the microstructure in the bathymetry can lead to substantial errors in the predicted return. Therefore, it has been proposed that bathymetric microstructure be included statistically in acoustic and sonar performance models just as sea floor material is included. Development of such a statistical tool is a goal of future research.

Likewise, the simplifying approximation used in many acoustic models that all bathymetric features are encountered head-on, i.e. that the acoustic path is perpendicular to the sand wave crest, is acknowledged to be faulty. This simplifying approximation is made primarily because extending the problem to three dimensions, as required to include azimuth angle effects, increases the complexity of the problem and computational time beyond the realm of reason for most acoustic models. However, to adequately represent the sea floor, azimuth angle effects cannot be ignored. In the cases studied here, the difference in backscattered acoustic intensity ranged from 15 to 50 dB, depending on the sand wave symmetry and dip angle, as the azimuth angle goes from 0 to 15 degrees. The situation is even worst for higher azimuth angles, plus the differences between the azimuth angle of 0 to 15 degrees increase with increasing dip angle. Figure 2 shows the effect of dip and azimuth angles on a simple forward facing[1] asymmetric (current or wave-current generated) sand wave or mega ripple. The sample sand wave has $\lambda = 2.0$ m,



2. Comparison of the results of varying azimuth and dip angle for a forward facing asymmetric sand wave. Displayed azimuth angles are 0^o (black), 15^o (red), 30^o (green), 45^o (yellow), 60^o (blue), and 75^o (violet). Sample sand wave/mega ripple has $\lambda = 2.0$ m, $\eta = 0.1$ and a.) dip angle = 30^o and b.) dip angle = 60^o

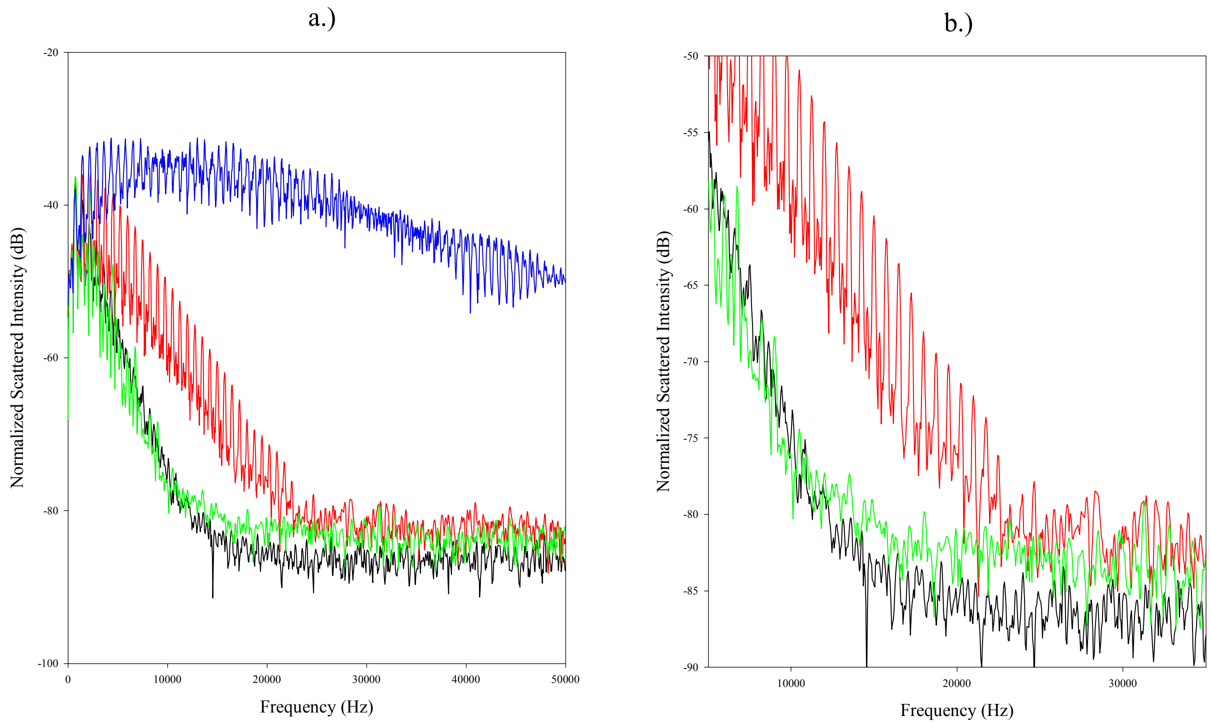
[1] In this context forward facing means that the current flows in the observation direction which is defined as the direction of increasing x. In other words, the lee slope of the sand wave is away from an observer placed at the origin of the coordinate system.

$\eta = 0.1$ and is shown for the cases of dip angles = 30° and 60°. This variation is clearly not insignificant. The question then becomes one of how to account for azimuth angle effects in the modeling. As with microroughness, it is believed that this parameter can be included statistically in the modeling as long as patterns in the results related to azimuth angle can be identified and quantified.

It is important to note that long-crested sand waves constitute the worst case scenario. Other sand wave patterns will not show quite as much variation since most will have part of a face towards the observer at all times. In these cases the amount of azimuth angle variation will be related directly to the percentage of sea floor that is encountered in a quasi-head-on manner. However, there are significant azimuth angle effects even for cuspate, i.e. horseshoe shaped, sand waves that at all times have a part of the sand wave crest towards the observer. The only times to date that little to no azimuth angle effects were observed in the modeling occurred when the base sand waves were overlaid with purely random microstructure. It's possible that some azimuth angle effects will be observed even for these very "noisy" sand waves when more simulations are included in the averaging.

The question of contributions from sonar side lobes arises from the observation that there are substantial differences between the head on backscattered return and that of other azimuth angles. If the sonar is oriented in such a way that a side lobe impacts the sand waves from the 0° azimuth angle, but the main lobe is off set, what is the probability that the return from the side lobe is significant? The answer lies in a comparison of the relative strengths of the main and side lobe with the relative variation in the backscattered acoustic intensity with azimuth angle. In this case, the assumption holds up. Sonar side lobes are typically 15 to 30 degrees off set with respect to the main beam and 50 to 80 dB down in relative strength. Therefore, except in some limited cases even a side lobe intersecting a sand wave head on will be down at least 20 dB from the main lobe backscattered return.

The final assumption or approximation considered here is the root mean square approximation. This assumption is that all sand waves can be approximated using a sine wave for the profile pattern. Figure 1 shows a comparison of the four sand wave profile patterns used in this study. They are pure sine wave (black), wave-generated symmetric (red), forward facing current/wave-current generated asymmetric (green) and backward facing current/wave-current generated asymmetric (blue). Their relative backscattered intensities for a dip angle of 30° are shown in Figure 3a. Clearly the sine wave backscattered return is not within 6 dB of the return from the backward facing asymmetric wave, but it much closer to some of the other profile patterned waves. Figure 3b shows an expansion of the pertinent range of frequencies from this study. It shows that there are some situations in which the rms approximation is valid, but in several others it is not. Other dip angles have greater agreement between the sine wave and backward facing asymmetric sand wave. For a dip angle of 45°, in the frequency range of 20 to 35 kHz, the returns from all sample profiles are within 15 dB of one another. At the dip angle of 60° the range of frequencies with reasonable agreement starts around 10 kHz and runs to around 35 kHz. Although this assumption holds in some situations, the agreement in general is not good enough to fully support the approximation. Another difficulty with the sine wave approximation



3. Comparison of the 0^{o} azimuth angle of the four sand model profiles, $\lambda = 2.0$ m, $\eta = 0.1$. Dip angle is 30^{o}.

for sand waves, is that some sand wave patterns are inherently asymmetric, such as cuspate and linguoid, and the rms approximation is inaddequate for them.

The modeling has clearly shown that the microstructure of the sea floor cannot be neglected. This holds regardless of the sand wave pattern considered. Similarly, azimuth angle can have significant influences on the backscattered return. This is particularly true for very directional sand waves, but also holds for more involved sand waves. However, as the randomness of the sea floor is increased, the variation with azimuth angle is reduced. A roughness parameter that can be used to statistically categorize sea floors so that their response can be reduced to a single number included with the sea floor material as an input to acoustic and sonar prediction models is being developed. The roughness parameter will take into consideration the fact that more random sea floors result in higher relative backscattered intensities, applying a higher scattering parameter to the sea floor material than might be expected.

The rms approximation, the assumption that all sand wave profiles can be approximated using a sine wave, is not fully supported. At some frequencies, the sine wave backscattered intensity is within the 6 dB window for consistency for three of the sand wave profiles considered. At others, the backscattered returns are quite different. The primary differences in the returns came when the sand wave slope towards the observer is much steeper than the corresponding sine wave slope. This suggests that a simple matter of comparing the facing slope of a sand wave with the sine wave will determine when the rms approximation can be successfully used. One advantage of the rms approximation over deterministic models such as BaGM is that the rms crest lines better represent the small variations along the crest than does a deterministic model like BaGM. The best solution seems to be a combination model that applies BaGM profiles to rms crest lines. This will work even for sand wave patterns that the rms approximation does not represent, such as cuspate and linguoid patterns.

This research showed that sonar side lobes do not contribute significantly to the backscattered intensity, even when conditions are favorable for a considerable return.

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